POWER-TO-GAS IN A DECARBONIZED EUROPEAN ENERGY SYSTEM BASED ON RENEWABLE ENERGY SOURCES
EXECUTIVE SUMMARY

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EXECUTIVE SUMMARY

The pan-European energy system is faced with the enormous challenge of lowering carbon emissions from electricity supply to nearly zero by 2050. This goes hand in hand with the need to integrate massive amounts of renewable energy sources (RES), mainly wind and solar power. The variable nature of these renewable energy sources makes it increasingly difficult to match electricity production and demand.

Power-to-gas is a compelling concept that converges the existing siloed value chains of the gas and electricity sector into one energy system able to meet the challenges of a mostly renewables-based energy supply system. It entails the conversion of surplus renewable electricity into hydrogen (H₂) via electrolysis. As hydrogen (H₂) can be re-electrified with high efficiency in fuel cells or combined cycle gas turbines, the power-to-gas concept can be used as a tool for network balancing and energy storage in a timescale of milliseconds up to and including seasons; however, when comparing the Levelised Cost of Energy (LCoE), power-to-gas is more likely to be used for long-term (seasonal) storage applications.

Next to the provision of flexibility to the power sector, power-to-gas enables optimized infrastructure investments that are necessary to integrate large amounts of fluctuating renewables into the energy system. Furthermore, it provides the following functionalities:

- It reduces the need to extend and upgrade the electricity network to transport large amounts of locally produced energy to other locations, by making use of capacity in the existing gas networks. This energy can be stored long-term.
- The produced hydrogen (H₂) is a carbon-free fuel and feedstock that can support the decarbonization of the transport sector and energy intensive industries.
- Power-to-gas helps to reduce the carbon intensity of the gas sector thereby ensuring its relevance for the future energy supply.

From a technological perspective, power-to-gas is ready for commercial exploitation. However, the challenge is to quickly reach an industrial scale that is economically exploitable. This depends heavily on the market conditions for the different applications of power-to-gas. For many of the above mentioned functionalities of power-to-gas there is currently not yet a business case. Significant cost reductions and efficiency improvements are required to enable its deployment on commercial scale.

From our perspective, the transport sector is key to the commercialization of power-to-gas. If for instance the national targets of EU member states for hydrogen (H₂) mobility are realized by around 2030 and all hydrogen (H₂) was to be supplied by power-to-gas installations, reductions in capital expenditure (capex) costs for electrolyzers will reach the required levels to allow for positive business cases in the other types of applications.

For the commercial deployment of power-to-gas to be successful, close cooperation between all stakeholders will be essential. Governments and regulators play an important role in creating a level-playing-field for power-to-gas; among other things, this includes acknowledging (green) hydrogen (H₂) as a biofuel, a comparable stimulation of hydrogen (H₂) mobility to electromobility, and eliminating all end user charges for the converted electricity. The gas and electricity sectors need to coordinate their network development plans with each other and end users need to adapt to the new fuel (blends).

The European Power to Gas Platform facilitates the dialogue between all these stakeholders. We provide them with a forum to gain and exchange knowledge and to explore the conditions under which power-to-gas can be successful, and provide assistance for setting up projects. Our common goal is to realize the energy transition as cost-effectively as possible.
During the 2015 United Nations Climate Change Conference in Paris (COP21), delegates from 198 countries adopted the collective aim to limit global warming to well below 2°C. If the 1.5°C target is to be achieved, greenhouse gas (GHG) emissions must be brought down to zero between 2045 and 2060. If Carbon Capture and Storage (CCS) technology is not applied to achieve this, the combustion of fossil energy carriers must be completely stopped by that time and the energy supply must be fully based on renewable energy sources (RES).

Already in October 2009, the European Council set itself the target to reduce GHG emissions by 80% below 1990 levels. The power sector will need to contribute higher abatements than other sectors according to the EU Reference Scenario 2016.6 If the 1.5°C target is to be achieved, greenhouse gas (GHG) emissions must be brought down to zero between 2045 and 2060. If Carbon Capture and Storage (CCS) technology is not applied to achieve this, the combustion of fossil energy carriers must be completely stopped by that time and the energy supply must be fully based on renewable energy sources (RES).

As European member states are investing heavily in renewable generation, wind and solar being the dominant technologies, it is becoming increasingly difficult to keep production and demand in balance. As these renewable energy sources have capacity factors of below 50%,4 this requires an overcapacity leading to periods in which the supply of electricity exceeds the demand (over various regions). Despite that, there will still be situations in which the electricity generation cannot satisfy the demand. This can be solved by applying energy storage to shift consumption of the harvested energy over time.

The need for flexibility in the power system will increase as well as the need for large scale (terawatthours) energy storage to cope with the mismatch between production and demand over longer periods (seasons).

Germany had an installed capacity of 44.5 GW of wind turbines and 39.3 GW of solar power at the end of 2015. The average load profile in Germany fluctuates between 50 and 80 GW on a work day and 40 and 60 GW during weekends. When both renewable sources produce electricity at full capacity in periods of a lower load profile, there is surplus electricity generation. This situation occurred various times in 2015 resulting in 4.7 terawatthours (TWh) of electricity being curtailed (93% wind and solar power). The network operators had to pay compensations in total of €315 million (m). This amount is expected to increase in the coming years as grid extensions do not have the necessary velocity.

4. The following capacity factors can be considered for the European situation: offshore wind – 40%, onshore wind – 20–30% and solar – 10–15%.
1.3 Power-to-gas is a promising solution

The key challenge in achieving a carbon-neutral energy system is finding a solution for scalable energy storage. While batteries, pumped-hydro, flywheels and other technologies have their merits, none can offer seasonal storage at a terawatt-hour scale. Power-to-gas is an innovative concept that couples the electricity and gas networks allowing for the flexible handling of excess and shortage of electricity generation.

The power-to-gas concept is about converting electrical power into a gaseous energy carrier such as hydrogen (H₂) and/or methane (CH₄). Its core components is an electrolysis cell in which water molecules are split into hydrogen (H₂) and oxygen (O₂) by applying an electric current. Next to the electrolysis cells, electrolyser units comprise auxiliary equipment such as a water demineralization unit, a water pump, a converter, a cooling system, a hydrogen purifier and control systems.

Through this process, electrical energy is converted to chemical energy in the form of hydrogen (H₂). The hydrogen (H₂) can be either used directly as feedstock or fuel in the industrial or transport sector. The hydrogen will be elated through the natural gas network via blending (and stored in gas storages) or further converted to methane (CH₄) via a methanation process by making use of captured carbon dioxide (CO₂). This may happen through, for instance, industrial flue gas or biological carbon sources such as biogas. Subsequently, the synthetic methane (CH₄) can be used in all natural gas end use appliances, for instance in mobility and residential heating. The graph below further illustrates the different power-to-gas pathways.

![Schematic representation of the power-to-gas concept](image-url)
2. POWER-TO-GAS AS A PROMISING MULTI-PURPOSE TOOL

The shift in the European power sector towards renewable energies calls for innovations that allow a decoupling of electricity production and demand. Chemical storage systems such as power-to-gas have the potential to become a sustainable and realistic solution to this need. In addition, chemical storage systems open new markets for surplus electricity by producing a carbon-free energy carrier and intermediate chemical product which can be applied outside of the power sector. In this White Paper, we explore the following functionalities of power-to-gas:

Balancing function - power-to-gas enables the high deployment of variable electricity sources

Energy storage - power-to-gas facilitates long-term energy storage on TWh-scale

Sustainable feedstock - power-to-gas supports the decarbonization of chemical and processing industries

Sustainable fuel - power-to-gas enables the decarbonization of the transport sector

Optimizing network investments and decarbonizing the gas sector - power-to-gas prevents overinvestments in the electricity network and reduces the carbon intensity of the gas sector

2.1 Power-to-gas provides flexibility to the power market

Volatility in power generation creates the need for rapidly available ramp-up and -down grid resources on both small and large scale. Electricity balancing services such as frequency containment reserves (FCR, also known as primary frequency control) are essential for a safe operation of the power system. Up to now this service is usually provided by conventional power plants. However, the increasing penetration of renewable energy sources and the parallel reduction of conventional power plants require new concepts and providers for these system services.

Water electrolyzers are able to respond quickly to power load changes, even on a sub-second level for some recent technologies. This makes them suitable for providing negative frequency reserves by increasing output or positive reserves by reducing output. Electricity network operators could therefore use electrolyzers to balance supply and demand, and hence keep electrical networks stable.

The situation is especially acute in poorly (or even non-) interconnected systems with high RES penetration. Power-to-gas represents one potential tool for managing renewable power intermittency and surplus generation in these regions. With the help of rapid response electrolysis which is able to respond even on sub-second level, it captures renewable surplus power which otherwise would be wasted and converts it into a storable energy carrier - hydrogen (H₂) or methane (CH₄) - for later use.

European areas with low interconnection and high shares of renewables could be the early markets for the commercial deployment of power-to-gas, as back-up generation is often much more expensive, especially when fuel oil or diesel are used.

2.2 Power-to-gas facilitates long-term energy storage on terawatthour-scale

The function of storage in the energy system is to shift energy consumption in time, ranging from minute level to several months. Underground Gas Storages (UGS) and Pumped Hydro Energy Storage (PHES) are considered important options to store energy on a large-scale and for longer periods (weeks to seasons).

In a deeply decarbonized electricity supply as envisioned by the EU, UGS facilities will play a crucial role for granting security of supply. Introducing wind and solar power into the energy system requires additional storage to counter their variable nature. Energy storage systems can provide a certain flexibility of the system by shifting load in time.

A key challenge for countries with strong seasonal energy demand patterns is how to bridge the gap between summer production and winter demand. Moreover, a resilient energy supply requires strategic storage to meet supply disruptions and/or demand peaks due to severe weather events.

Ramea island with three 100 kW wind turbines in the background that form part of the power-to-gas installation; Source: Nalcor Energy, 2010+
Power-to-gas could offer a means to facilitate large-scale and long-term energy storage by transforming renewable electricity, when produced in excess, into a storable energy carrier - hydrogen (H₂) or methane (CH₄) - and by making use of the existing storage capacities of UGS facilities.

2.3 Power-to-gas provides sustainable feedstock for chemical and processing industries

The process industry represents 20% of the total European manufacturing industry in terms of employment and turnover. More than 25% of Europe’s total energy consumption in 2010 is attributed to industries of which a significant portion is used within the (energy intensive) process industry.7

To be able to reach the EU’s long-term climate objective of achieving economy-wide emission reductions of 80% by 2050, the (process) industry is expected to become more sustainable and to reduce its carbon footprint. This requires a radical improvement in efficiency for both energy and feedstock use, and deep decarbonization to sustain the chemical industries’ licence to operate in a low-carbon economy.

Sustainably produced hydrogen (H₂) from renewable electricity is a carbon-free energy carrier and chemical intermediate product that can contribute to the abatement of carbon dioxide (CO₂) emissions in, for example, metal and glass manufacturing, chemical industries and refineries. For instance, it can be combined with carbon dioxide (CO₂) and nitrogen (N₂) to produce a range of (sustainable) products such as methanol, ethylene and ammonia. However, production of hydrogen (H₂) by electrolysis is generally still more costly than production from natural gas.

One of the challenges of industrial decarbonization is the commercial availability of low-carbon process technologies (such as large-scale electrolysis). These new process technologies will need to be market-ready by 2030 to allow for deployment across the EU by 2050.8

2.4 Power-to-gas enables the decarbonization of the transport sector

EU legislation requires the GHG intensity of vehicle fuels to be cut by 6% and to deliver 10% per cent of the energy in transport from renewable sources by 2020.9,10 Both requirements promote the use of biofuels. Although the Renewable Energy Directive (RED) set out sustainability criteria for all biofuels produced or consumed in the EU to ensure a sustainable and environmentally friendly production manner, policy debates have intensified over the last years about whether biofuels deliver sufficient GHG savings to justify substantive support. In particular, the potential negative impacts related to Indirect Land Use Change (ILUC) and increasing food prices are subject to concerns.

As a result of these debates, the European Commission’s vision for a climate and energy framework beyond 2020 does not, until now, include any new targets for renewable energy or GHG intensity of fuels used in the transport sector. However, as part of the European “Clean Energy for All Europeans” package, the Commission set out the target of achieving a 70% reduction in GHG emissions by 2050. If biofuels are no longer going to form a strong pillar of a low-carbon future for transport, other renewable energy carriers need to play a more prominent role. Next to electromobility, green hydrogen (H₂) can fulfil that role.

9. Source: www.carbonrecycling.is
Similarly, in the maritime sector a window of opportunity is opening for power-to-gas. Marine shipping is increasingly pushed towards lower emissions of harmful pollutants; especially since the implementation of stricter regulations (Revision of Annex VI to the International Convention for the Prevention of Pollution from Ships, in force since July 2010). The restrictions with respect to allowed sulphur emission levels increasingly limit the use of fuel oil and require for a shift towards cleaner fuels. Next to liquefied natural gas (LNG), electric propulsion powered by fuel cells has gained the most attention. Power generation via fuel cells on-board ships not only decreases the emission of harmful pollutants, but also increases the efficiency of the facility.

A Norwegian project is aimed at demonstrating the feasibility of using hydrogen (H₂) fuel cells for marine application. A car ferry will be equipped with an electric motor powered by 200kW PEM fuel cells in combination with 100 kW batteries.

The 150 kg hydrogen (H₂) per day will be supplied by a power-to-gas facility using electricity from the Norwegian grid (97% renewable). Expected fuel costs are between €2.8-4.5/kWh. For comparison: conventionally produced hydrogen via steam methane reformation costs 1.5-2.5 €/kg H₂.12

In Iceland's capital Reykjavik, three fuel cell buses began operating in autumn 2003 supplied with hydrogen (H₂) produced via electrolysis. The electricity consumed in the electrolyser comes from geothermal (20%) and hydropower (80%). Nowadays, the refuelling station not only serves buses but also two dozen of hydrogen-powered passenger cars.

In the first quarter of 2017, the French company Alstom tested the world's first low-floor hydrogen-fuelled train which is expected to operate regularly in Lower Saxony (Germany) at the beginning of 2018.

The Coradia iLint can reach speeds of up to 140km/h. For the purpose of the tests, a mobile filling station has been erected supplying hydrogen (H₂) that is a by-product of an industrial process. In the long term, Alstom aims to support the hydrogen (H₂)-production with wind energy.

In September 2016, the first hydrogen fuelled airplane, known as HY4, was tested. The plane was developed in a collaboration between Pipistrel, the fuel cell specialist Hydrogenics, the University of Ulm and the German Aerospace Center DLR.

Four low temperature PEM fuel cells generate electricity, giving it a cruising speed of 165km/h and a range of up to 1,500km. It can carry four passengers (including the pilots).

Each fuselage contains a 9kg hydrogen (H₂) storage tank that feeds the fuel cell modules.

In a recently published report that, in specific situations, power-to-gas has the potential to optimize a set of network extensions that were proposed by the European research project, e-Highway2050. By substituting parts of the planned extension capacities between the Netherlands and Norway, the simulations showed a cost decrease of more than a billion euro annually.

A study of FENES for Greenpeace Energy in 2015 estimated the system cost benefits of using power-to-gas in Germany in 2050. A 100% renewables-based energy system with power-to-gas would cost €12-18 billion per year compared to a system using existing natural gas. Power-to-gas can help the gas sector decarbonize its commodity and sustain the continued use of the gas infrastructure even in a low-carbon economy.

Another study financed by the Hydrogen Fuel Cell Joint Undertaking and elaborated by a consortium of 32 industry stakeholders and research institutes analysed that, even in a highly interconnected European energy system with high RES penetration in 2050, there is a potential of hundreds of GWs of electrolyser capacity to deal with the excess renewable electricity.16

The power-to-gas concept also offers new opportunities for the conventional European gas sector which is increasingly under pressure due to the transition towards a renewables-based energy supply. On the one hand, the substitution of existing heating systems with more energy efficient technologies, as well as the trend towards low-carbon heat supply (e.g. with solar thermal or geothermal heat sources), reduces the sales prospects of natural gas in the residential market. On the other hand, increasing shares of renewable electricity have led to depressed power spot prices that are paid efficiently gas-fired power plants struggle to compete with wind and solar power plants. Thus, gas supply to the power sector is declining as well. Power-to-gas can help the gas sector decarbonize its commodity and sustain the continued use of the gas infrastructure even in a low-carbon energy supply.

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16. Source: http://www.dlr.de/de/tech/dein_energiehandbuch/100811511_read-192460103e24060
3. THE ECONOMIC VALUE OF POWER-TO-GAS

The previous chapter introduced the services of power-to-gas. In this chapter we want to give an overview of the economic potential that power-to-gas offers to the different sectors. In many cases it is not a straight-forward task to quantify the economic potential; nevertheless, the following sections give an indication of the range of order.

3.1 Value of power-to-gas for balancing services

Network balancing services are valued at a transmission, and increasingly at a distribution level. Approximately 3,000 MW of Frequency Containment Reserve (FCR) capacity is currently available in the synchronous area of Continental Europe. This category typically includes operating reserves with an activation time of up to 30 seconds. FCR is mainly provided by conventional power plants with inertia in their rotating equipment (such as generators). In 2013, Germany started to tender for FCR and, over the last three years, Switzerland, the Netherlands, Austria, Denmark and France have joined in. Meanwhile, approximately half of the FCR capacity in Europe is tendered with the effect that prices, and therefore balancing costs for the transmission system operators, have decreased significantly (see also figure below).


With increasing shares of renewables, the share of conventional power plants will decrease and with it the available FCR capacity. Rapid response electrolysers could take over a part of this service, providing network stability and maintaining a competitive FCR market in the future.

3.2 Value of power-to-gas as a means of energy storage

The energy storage functionality of power-to-gas can be applied at different scales varying from small-scale applications that balance the output of a single wind turbine to large-scale storage on system level. Power-to-gas is also very flexible with respect to the duration of an energy storage cycle; because of its technical ability to respond quickly to load changes it can even be used for short (charge and discharge) cycles of less than one hour. However, in order to determine the value of the power-to-gas concept for the power sector, one has to consider the (existing and potential) competitors for the services that power-to-gas can provide. A good means for comparing the different energy storage technologies is the widely recognized Levelized Cost of Energy (LCoE) methodology. It is an economic assessment of the average total cost to build and operate an asset that generates (or in this case stores) energy divided by the total energy output over its lifetime.

A study published by McKinsey and The Hydrogen Fuel Cell Joint Undertaking showed that if power-to-gas was to be installed for short-term storage with a (charging and discharging) cycle duration between 1-8 hours, it would have to compete with Pumped Hydro Energy Storage (PHES).

Compressed Air Energy Storage (CAES) and batteries which all not only feature much higher round-trip efficiencies, but also much lower LCoE than power-to-gas. Nevertheless, the most cost-effective technology for long-term energy storage resulted to be hydrogen production via PtG, storage it in a salt cavern and re-electrification by combustion in a turbine with a LCoE in the order of EUR 140/MWh (this case calculates with a cycle duration of more than 2,000 hours). For comparison, PHES has a LCoE of > €400/MWh for the same cycle duration.20

The comparably lower costs for long-term storage of energy via power-to-gas in comparison to its competitors is also confirmed by a recent LCoE analysis carried out by DNV GL for storage cycles of two weeks and more, power-to-gas proved to be the most cost effective technology (see also figure below).

The potential of power-to-gas as energy storage means is also recognized in a recently published working document of the European Commission stating that: “the cost of large-scale long-term storage of hydrogen (and related chemicals) is already very low, especially in underground caverns, making it the most cost-efficient technology for long-term storage. This longer storage timeframe reflects also the potential for cost-efficient sectorial integration.”21

![Indicative comparison of LCoE for Li-ion batteries, CAES, PHES and power-to-gas with underground hydrogen storage and re-electrification in a gas turbine taking into account different energy to power ratios (Installed capacity [kWh] divided by rated power [kW]). The LCoE analysis did not consider the cost of charging the storage systems; Source: DNV GL on the basis of data from Zäké et al., 201523 and WECS, 201624](https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Technical_Publications/Dutch2016_Market_Review_TenneT.pdf)


23. World Energy Council (2014), World Energy Resources – E-storage: Shifting from cost to value (Wind and solar applications)
The costs for hydrogen ($H_2$) delivery via tube trailers to small industries is already comparable to the costs of hydrogen ($H_2$) from power-to-gas installations. In the medium (2030) and long term (2050), green hydrogen ($H_2$) from onsite electrolysis will become competitive to delivered hydrogen ($H_2$). For large scale applications, opportunities to generate cheaper green hydrogen ($H_2$) from electrolysis will emerge before 2050, taking advantage of the lowest electricity prices. This, however, excludes base load operation.

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3.3 Value of power-to-gas for chemical and processing industries

According to a power-to-gas potential study carried out in 2016, the supply of large industries with hydrogen ($H_2$) from power-to-gas installations currently costs approximately twice as much compared to the conventional (steam methane reforming, SMR) production process. The price spread will decrease in the long term if carbon dioxide ($CO_2$) allowances rise in price and power-to-gas capex decreases.24

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3.4 Value of power-to-gas for the transport sector

An additional market that could evolve for green hydrogen ($H_2$) in the next decade is the transport sector; projections based on current hydrogen-mobility programs of various European countries result in a maximum of 0.5Mtons hydrogen ($H_2$) demand in 2030.26 When supplying all that hydrogen ($H_2$) with power-to-gas installations, an installed electrolyser capacity of 8.5GWel would be required (at a capacity factor of 30%). When applying a very conservative learning rate of 5% (solar PV panels had a learning rate of 20-25%), this quantity has the potential to lower electrolyser capex costs by more than two thirds until 2030.27

The transport sector represents the most promising application for the use of green hydrogen ($H_2$) at the moment and could be the first target for large scale deployment of the technology. The cost of hydrogen ($H_2$) produced from electricity is already comparable with other green fuel options; current levelised costs of €8-10/kgH2 of distributed hydrogen ($H_2$) already compete with compressed biogas (bioCNG) on a fuel cost per kilometre basis.27 To become competitive with fossil fuels such as petrol, hydrogen ($H_2$) produced via power-to-gas will have to be delivered at a levelised cost of €3-4/kg.


4. TECHNICAL DEVELOPMENTS WILL IMPROVE THE BUSINESS CASE AND ENABLE EXTENDED OPERATING ENVELOPES

4.1 Readiness of power-to-gas technology

As can be seen in the figure below, crucial components of the power-to-gas value chain such as Proton Exchange Membrane (PEM) electrolyzers, fuel cells, methanation, hydrogen (H₂) injection to natural gas networks and storage in underground gas storages are still in the piloting or demonstration stage.

The power-to-gas value chain consists of different (technical) components featuring different levels of technological readiness. The following paragraphs highlight the state of the art and developments for the crucial components of the power-to-gas value chain such as hydrogen (H₂) production via electrolysis to processing via methanation to hydrogen (H₂) injection into the natural gas grid.

4.2 Power-to-gas demonstrations in Europe

Since 2012 there has been a steep increase in the number of demonstration plants, with Germany as a leading nation in Europe. In the first quarter of 2017 a total number of 70 power-to-gas projects were realised or under way in Europe, all having a strong research or demonstration character. The large number of research and application projects helps the new technologies to outgrow laboratory conditions and brings them closer to commercial deployment.

By Q1 of 2017, the (realised) installed capacity of electrolyser totalled approximately 30MW. The vast majority is located in Germany, followed by Spain and the United Kingdom.

More than 60% of the power-to-gas projects have hydrogen (H₂) as final product, 23% methane (CH₄) and 15% both hydrogen (H₂) and methane (CH₄). Only one project produces methanol (CH₃OH).

In most of the projects the produced gas finds its destination in the natural gas network (33%). The transport sector and power generation as end users are targeted in 25% of the projects. One single project delivers gas to an industrial user.
4.3 Accelerated developments in the field of electrolyser and methanation technology

There are three types of electrolysis technologies that are predominantly considered for application in power-to-gas plants. Two of them are commercially available, namely alkaline electrolyzers (liquid electrolyte) and Proton Exchange Membrane (PEM) electrolyzers. The third one, solid oxide electrolysis has been proven on a laboratory scale but it is anticipated to become commercially available by 2020.

Until recently electrolysis (mostly alkaline electrolysis) has generally been applied for continuous industrial processes such as the production of fine chemicals or vehicle fuel and can be characterized as mature. Both these applications, however, did not require the electrolysis process to be very flexible for its application in terms of ramping up or down. With the increasing penetration of variable renewable energy resources the need for demand-response operational regimes evolved. The units had therefore to be adapted making them suitable for stop-start, efficient part-load and dynamic operation. For alkaline electrolyser technology, the modifications have been demonstrated and validated in field tests already. The PEM technology used to be applied in small-scales in niche markets. Units of larger scale (max. 2 MW(e)) have recently been released and are currently under demonstration. Although the investment costs are still higher compared to alkaline electrolyzers, PEM electrolyzers have a better long-term perspective due to higher compactness, efficiencies and expected cost reductions than alkaline technology.

Solid oxide electrolyzers operate at significantly higher temperatures than alkaline, PEM and AEM electrolyzers, typically at 500-850°C. This reduces the electrical input required for the electrolysis reaction. High temperature resistant ceramic materials are used as electrolyte and electrode materials.

Technology development priorities vary among the different electrolyser types. Generally, they respond to the need to reduce cost while maintaining or improving performance. Based on stakeholder opinions, the system sizes and efficiencies will increase significantly (3% improvement for alkaline and 8% for PEM). The system costs of alkaline electrolyzers are expected to decrease by 30% and for PEM electrolyzers by 50% by 2030. If all predicted hydrogen demand in the mobility sector by that time would be supplied by electrolysers, this cost reduction would already be achieved.

Solid oxide electrolysis still needs to be proven on a commercial scale however. Next to improvements with respect to lifetime lower degradation rates, also a minimum operational flexibility is required.

4.4 Injection of hydrogen (H₂) into gas networks

The existing natural gas pipeline system provides an infrastructure that could potentially be used for transporting hydrogen (H₂) in the form of a hydrogen-natural gas blend. Natural gas pipelines are widespread and highly interconnected throughout Europe offering a means for safe and large-capacity transmission.

Because the physical and chemical properties of hydrogen (H₂) are different from natural gas, the permissible hydrogen (H₂) fraction is limited to ensure the safety, operability and quality of the gas system. Pipelines used in the natural gas grid have not been designed to withstand the specific properties of hydrogen (H₂) such as higher permeation and corrosion. Research studies have suggested that volume fractions of up to 20% could be tolerated without much modifications of the infrastructure. However, end use appliances for natural gas often show lower hydrogen (H₂) tolerances, which is why most European standards are below 5%. Research and analysis is in progress by various entities to determine appropriate blending limits.

There are several projects in Europe demonstrating that hydrogen-natural gas blends can be safely transported and used by end user appliances. Some of these projects are:

- **GRHYD** is demonstrating hydrogen-natural gas blends of 6-20% H₂ in refuelling station and a fleet of around 50 buses. In addition, a residential area of around 200 homes will be supplied with a hydrogen-natural gas blend with a variable H₂ content of <20%.
- **HYDEPLOY** will demonstrate that a hydrogen-natural gas blend of 10-20% can be safely transported by Keele University’s private gas network and used by the consumers.
- **H21 LEEDS City Gate** aims at determining the feasibility of converting the existing natural gas network supplying the city of Leeds to 100% hydrogen (H₂).
- **JUPITER 1000** will inject up to 5% hydrogen (H₂) into the transmission gas grid in France.
- **HYREADY** is developing guidelines and recommended practices for network operators to prepare their assets for H₂ injection in their natural gas networks.

![Expected development of capex and efficiencies of alkaline and PEM electrolysers based on stakeholder consultation](image)

30. 0.5 Mton hydrogen demand predicted by Certighy (2015). Market outlook for Green Hydrogen. Cost reduction from £1.5 to £0.7 /kW at a 5% cost decrease with each doubling of the installed capacity.
4.5 Methanation

Methanation refers to the synthesis of methane (CH₄) by hydrogenation of carbon monoxide and is basically a process to synthetically produce natural gas. The carbon dioxide (CO₂) required for methanation can either be obtained from biogenic carbon sources as for instance biogas, or captured carbon dioxide (CO₂) from industrial processes (e.g. production of steel, cement and lime). The produced gas can thus be integrated into the natural gas infrastructure without restrictions.

Methanation itself is a mature technology that is already being widely applied in industrial processes such as ammonia synthesis. In order to be suitable for power-to-gas applications, methanation units need to be downscaled and adapted to intermittent operational regimes; that is why methanation is currently also tested in various power-to-gas demonstration plants.

Catalytic methanation is a thermochemical process; the reaction takes place by use of a catalyst. Nickel is often chosen as a catalyst because of the favourable costs relative to other precious metals. The process takes place at two temperature ranges: low temperature methanation in the range of 200–550°C and high temperature methanation between 555–750°C. Cost figures available on capex show high spreads between €400-1,500/kWₑₑₑ due to the lack of units under commercial operation so far. When the market for small-scale methanation develops, it is expected that these units can be purchased for €300-500/kWₑₑₑ.

As an alternative to chemical methanation, biological methanation converts hydrogen (H₂) together with carbon dioxide (CO₂) to methane (CH₄) using methanogenic microorganisms operating as bio-catalysts. The reaction occurs under anaerobic conditions in an aqueous solution, at atmospheric pressure or under pressure, between 20 and 70°C. Biological methanation has the potential to reduce costs thanks to a simpler reactor design and convenient pressure and temperature conditions. The concept is currently demonstrated in Denmark in a power-to-gas plant featuring a 1MWₑₑₑ electrolyser. The stability, response time and ramp-up and down of the process is thoroughly tested.

Methanation is an additional conversion step in the power-to-gas process and thus means a further loss of efficiency. However, methanation can be a solution in situations where H₂ either cannot be used on or close to the production site nor be injected into the gas network. Besides, the biological methanation process can be applied as an upgrading process where the carbon dioxide (CO₂) in the raw biogas is directly used as a carbon source. A combined deployment of power-to-gas installations and anaerobic digestion is especially interesting for wastewater treatment plants; not only can the biogas output be increased by converting the carbon dioxide (CO₂) in the biogas into methane (CH₄), but also the oxygen (O₂) produced in the electrolyser can be applied in the treatment processes of the wastewater. In this way, synergies can be developed and the efficiency of the overall process can be increased.

5. BARRIERS

To fully utilize the potential of power-to-gas, large-scale technology implementation should be accelerated so the costs are driven down. To achieve this, several barriers need to be overcome. The table below presents the challenges that were identified and gives suggestions how these could be tackled.

<table>
<thead>
<tr>
<th>CHALLENGES</th>
<th>REQUIRED ACTION</th>
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<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>- PEM electrolysers need to become quickly available on multi-MW scale. - Increase expected lifetime of cell stacks of electrolysers. - Solid oxide electrolysers need to be proven on commercial scale. - Uncertainties about risks and impact of hydrogen-natural gas blends on end use equipment and underground gas storages need to be taken away.</td>
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<tr>
<td><strong>Economics</strong></td>
<td>- For the application as large-scale energy storage the renewable’s share is not high enough yet to guarantee sufficient annual operational hours. - High capex this does not allow for positive business cases yet. - The prices of carbon dioxide (CO₂) emission allowances are too low.</td>
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<tr>
<td><strong>Regulation</strong></td>
<td>- Hydrogen (H₂) and methane (CH₄) produced from renewable electricity are not yet recognized by the European Commission as ‘biofuel’ and therefore are not accountable for reaching the renewables target in the mobility sector. - In several countries power-to-gas is treated as power end use which entails that taxes and fees need to be paid by the plant operators for purchasing electricity. - Currently there is no Green Hydrogen Certification scheme in place. - Not all European countries allow load shedding as balancing service.</td>
</tr>
<tr>
<td><strong>Collaboration</strong></td>
<td>- Power-to-gas must be considered as complimentary option to electricity network extensions. This requires for a close collaboration of the electricity and gas sector which does not come naturally.</td>
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- Continued extension of renewable generation capacity following the EU renewables targets for 2020 and 2030. - Establishing a competitive market for carbon dioxide (CO₂) allowances that stimulates investments in low-carbon technologies. - Focussing on projects where business case is (near to) positive. - Recognize hydrogen (H₂) from renewable electricity as renewable fuel which is accountable for the biofuel quota and establish a certification scheme for ‘green’ hydrogen (H₂). - Continued policy of renewable fuel quorum for mobility sector after 2020. - Allow load shedding as balancing service which would create an additional income for the operators of electrolysers, reducing hydrogen (H₂) production costs. - Consideration of the power-to-gas concept as complimentary option to electricity network extensions.
Power-to-gas is an innovative concept that will converge the existing siloed value chains of the gas and electricity sector into one energy system which is able to meet the challenges of a mostly renewables-based energy supply system.

In principle, power-to-gas is technologically already in an advanced stage, with single components and their interplay currently being refined and optimized to prepare for the market launch. The challenge is to quickly reach an industrial scale of the technology that is economically exploitable. This is a typical chicken-and-egg problem as industrial scale technology is only installed when low equipment costs allow for a positive business case and low equipment costs in turn are only achieved with mass production.

There are some solutions to this dilemma. To begin with, power-to-gas needs to be installed in cases where it is already (near to) profitable. These cases are:

- Islands and poorly connected regions with high variable RES shares and expensive back-up systems
- Regions with high/excess cheap (renewable) electricity production that can be converted into hydrogen (H₂) for use in the mobility sector
- Small-scale industry applications for hydrogen (H₂) supply (instead of tube trailer delivery)

The successful exploitation of power-to-gas in those cases together with continuous cost reductions and efficiency improvements would enable the industrial scale development of the technology.

From our perspective, the transport sector is key to the commercialization of power-to-gas. If the national targets for hydrogen (H₂) mobility for 2030 are realized, capex cost reductions for electrolyzers will reach the required levels to allow for positive business cases in other types of applications.

With time, the share of variable renewable electricity sources in the energy mix will progress towards the EU sustainability targets calling for large volume and long-term energy storage options to mitigate their fluctuations. Currently, there is no energy storage technology that can compete capacity and cost wise with power-to-gas when it comes to storing energy over longer periods. Other factors that improve the business case for the power-to-gas concept are:

- Increasing necessity for deep decarbonization in the mobility sector and energy-intensive industries
- Optimized infrastructure investments achieved by coupling the electricity and gas networks
- Higher price of carbon dioxide (CO₂) emission allowances.

For successful commercial deployment of power-to-gas, a close cooperation between all stakeholders is essential. Governments and regulators play an important role in creating a level playing field for power-to-gas; among other things, this includes acknowledging (green) hydrogen (H₂) as biofuel, comparable stimulation of hydrogen (H₂) mobility as with electromobility, and eliminating all end user charges for the consumed electricity. The gas and electricity sector need to coordinate their network developments with each other and end users need to adapt to the new fuel (blends).

The European Power to Gas Platform facilitates the dialogue between all these stakeholders. We provide them with a forum to gain and exchange knowledge and explore the conditions under which power-to-gas can be successful and help to set up projects. Our common goal is to realize the energy transition as cost-effectively as possible.
The European Power to Gas Platform is a joint body, based on an integrated network of stakeholders, which aims to explore the viability of power-to-gas in Europe.

Learn more at: www.europeanpowertogas.com